

Advanced Beam-Dynamics Simulation Tools for the RIA Driver Linac/ Part 1: Low Energy Beam Transport and Radiofrequency Quadrupole

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Introduction

Understanding beam losses is important for the high-intensity RIA driver linac. Small fractional beam losses can produce radioactivation of the beamline components that can cause radiation damage to components and can hinder hands-on maintenance, reducing facility availability. Operational and alignment errors in RIA can lead to beam losses caused by irreversible beam-emittance growth and halo formation. These issues impact the tolerance specifications and aperture choices in the linac and beam transport sections, as well as the design of the stripper regions. We are developing beam-dynamics codes for RIA driver linac simulations extending from the low-energy beam transport (LEBT) line to the end of the linac. We intend that these codes will be particularly useful for computing the beam losses as well as for predicting the beam performance. These multiparticle simulation codes will be developed to run on parallel supercomputing platforms in anticipation of running simulations requiring large numbers of macroparticles for the beam-loss calculations. They will also be important for the optimization stage of the driver-linac design.

Overview

The present concept for the Rare Isotope Accelerator (RIA) project [1] includes a 1.4-GV superconducting driver linac operating with a 100% duty factor. The driver linac is designed for multicharge-state acceleration [2] of all stable species, including protons to 900 MeV and uranium to 400 MeV/u. In conventional heavy-ion linacs, a single charge-state beam of suitably high intensity is extracted from an electron-cyclotron resonance (ECR) ion source and injected into the linac. The linac typically contains one or more strippers at higher energies to further increase the beam charge state and improve acceleration efficiency. However, the limitation to a single charge state from the ion source and from each stripper significantly reduces the beam intensity. This disadvantage is addressed in the RIA driver-linac design concept by the innovative approach of simultaneous acceleration of multiple charge states of a given ion species, which results in high-power beams of several hundred kilowatts for all beams ranging from protons to uranium. Initial beam-dynamics studies [2], supported by experimental confirmation at the Argonne ATLAS facility [3], have demonstrated the feasibility of this new approach.

However, the high-power beam associated with the multiple charge-state acceleration introduces a new design constraint to control beam losses that cause radioactivation of the driver linac [4]. Radioactivation of the linac-beamline components will hinder routine maintenance and result in reduced availability of the facility. Therefore, it will be important for the RIA project to produce a robust beam-dynamics design of the driver linac that minimizes the threat of beam losses. As an important consequence of this design requirement, it will be necessary to develop a computer-simulation code with the capability of accurately modeling the beam dynamics throughout the linac and computing the beam losses, especially at high energies where beam loss translates into greater activation. To appreciate the scope of the requirements for this simulation code, it is necessary to review the RIA driver-linac design concept.

The driver linac is made up of three sections. The first is the pre-stripper accelerator section consisting of 1) an ECR ion source, and 2) a low-energy beam transport (LEBT) line, which includes a mass and charge-state-selection system, and a buncher/RFQ injection system. This is followed by the initial linac stage consisting of 3) a room-temperature radiofrequency-quadrupole linac, a medium-energy beam transport (MEBT) line, and 5) the low-velocity (low- β) superconducting accelerating structures. The pre-stripper section accelerates the beam, consisting of two charge states for uranium, to an energy of about 10 MeV/u, where the beam passes through the first stripper and new charge states are produced.

The second section of the linac uses medium- β superconducting structures to accelerate the multicharge-state beam from the first to the second stripper at an energy of about 85 MeV/u. This medium- β section accelerates about five charge states for uranium. This is followed by the third and final section of the linac, which uses high- β superconducting structures to accelerate typically four charge-states for uranium to a final energy of 400 MeV/u.

Following each stripper is a magnetic chicane section for charge state selection and matching of the multicharge beams to the superconducting linac. The chicanes contain magnetic lenses for transverse focusing and RF structures for longitudinal focusing. The beam may be collimated in the chicane region, where some part of the halo that could lead to subsequent beam losses can be removed.

The overall performance of the driver linac is crucially dependent on the performance of the LEBT and RFQ. The LEBT is designed to focus, bunch, and inject two charge states for uranium into alternate longitudinal buckets of the RFQ. The LEBT RF buncher system consists of two main components. The first RF buncher cavity system (multiharmonic buncher) uses four harmonics and is designed to capture 80% of each charge state within the longitudinal acceptance of the RFQ. A second RF buncher cavity matches the velocity of each charge state to the design velocity of the RFQ. The two charge states for uranium are injected into the RFQ in such a way that adjacent RF buckets contain alternate charge states.

To avoid problems from beam-induced radioactivation, beam losses must be limited to low values, particularly in the high-energy part of the accelerator, where the beam loss rate must be less than about 1 watt per meter [5, 6]. The low beam-loss requirement imposes a challenge for controlling the emittance growth throughout the driver-linac, especially because of the acceleration of multiple charge-state beams. In addition to increasing the intensity, acceleration of multiple charge-state beams produces a larger total longitudinal emittance, increasing the threat of beam losses. For any proposed design it is imperative to compute the high-energy beam losses to ensure that the beam-loss requirements are satisfied. Such a computation normally requires the use of simulation codes that accurately track the beam particles through the whole accelerator using a physics model that includes all effects that can lead to emittance growth and possible beam losses. The development of such a simulation tool with relatively fast turnaround is the primary objective of our proposal.

Previous Simulation Code Developments for RIA

A significant amount of accelerator design work has already been done at two institutions, Argonne National Laboratory (ANL) [5] and Michigan State University (MSU) [7]. At present for superconducting linac simulations, the code LANA [7, 8] is used at MSU, and the code TRACK [9] is used at ANL. The LANA code was used extensively during the design and commissioning of the radioactive beam linac ISAC-1 at TRIUMF [10]. It was benchmarked as a result of the commissioning measurements, and is also being used for the design of ISAC-II, a superconducting linac for production of ion beams with energies above the Coulomb barrier.

These codes integrate the particle equations of motion through the electric and magnetic fields of the superconducting cavities, the 3D field components having been obtained from numerical solution of Maxwell's equations for each specified cavity geometry. The codes follow the motion of the particles in 6D phase space, and generally represent the dynamics of the multicharge-state beam with good spatial resolution. The codes are user friendly; they are written in Fortran language, have a modular structure, and have good graphical support for use on a PC. The codes also allow one to study effects on the beam caused by random errors associated with mechanical misalignments of focusing elements and rf cavities, and field errors, especially phase and amplitude errors in the rf cavities [5, 11, 12].

Although much code development has already taken place for RIA, more work to develop faster end-to-end simulation tools will be important for accurate computation of beam losses. In addition, the importance of demonstrating an understanding of the beam-losses justifies the development of more than one such code to provide the necessary cross checks on the simulations.

Development Plans for a New RIA Simulation Code

The problem of computing beam losses under realistic conditions requires the introduction of random machine errors including misalignments and field errors. The

random error treatment is necessary for two reasons. First, in the as-built accelerator there are deviations of machine parameters from their exact design values, including errors in positioning of the beamline elements and field errors. Second, there are time fluctuations for some parameters, most notably the rf phase and amplitude of the superconducting cavities, which are driven by ambient mechanical vibrations (microphonics). This means that the problem of predicting the beam losses is inherently a statistical one. To be able to produce enough runs with a large enough number of particles, one needs to achieve fast turnaround. To accomplish this, we propose to develop a RIA beam-dynamics simulation code that runs in a parallel computing mode.

These simulation tools are important for computing beam losses for different RIA accelerator design options. At present an accelerator beam-dynamics design optimization process is already underway with several design options that are under development [5, 7, 13]. The simulation tools are important for the RIA project because they allow a fast and efficient capability for optimization of the machine design that properly addresses the beam-loss requirement. Since the beam-dynamics design must be completed at the earliest stages of the RIA project, this work addresses an important near-term need for the project.

We believe the quickest and most reliable way to produce the desired multiparticle simulation tools will be to use existing simulation codes as the starting point. The first code we will use is PARMTEQ [14], a Fortran code developed at LANL more than 20 years ago for simulation of low-energy ion beams in RFQs, and in low-energy beam transport lines both upstream and downstream of an RFQ. Thus, the PARMTEQ code can track particles through the low-energy beam transport (LEBT), the RFQ, and the medium-energy beam transport (MEBT). PARMTEQ provides an accurate RFQ model, calculating the beam dynamics in the RFQ using up to eight multipoles of the RFQ potential function. For beam simulations in the superconducting linac, we will use the IMPACT code [15], a Fortran code developed initially at LANL and more recently at LBNL. The IMPACT code already runs in parallel mode; the PARMTEQ code does not.

The LEBT region is modeled with the PARMTEQ code, and has a unique and rather complex set of requirements. The beam particles of both charge states are transported as a dc or continuous beam from the ion source to the buncher system. The design for uranium calls for two charge states, and both charge states must be matched and injected into the RFQ, so that alternate charge states are injected into adjacent buckets (separated by two cells). If desired, space-charge effects can be calculated by both the PARMTEQ and the IMPACT codes. We have assumed that space charge must be included in the LEBT and RFQ simulations at least, and the space-charge routine must be capable of handling both continuous beams and long bunches corresponding to beams in the process of being bunched. The standard version of PARMTEQ uses a 2D particle-in-cell space-charge subroutine called SCHEFF. SCHEFF has two versions, an X-Y version, which we are using, in the region of the LEBT where the beam is unbunched, and where the two charge states are horizontally separated, and the R-Z version, which is used where the beam is bunched or in the process of being bunched. These space charge subroutines are modified appropriately to represent the transverse and longitudinal space-charge effects

for beams with multiple charge states. Our initial plan is to modify PARMTEQ to handle two charge states; initial simulations can begin at the charge-state selection slit in the LEBT, where the two charge states are selected.

For the beam-loss computation, statistical distributions of the beam are obtained by accumulating the results of repeated simulations with different initial random number seeds. Enough runs must be made for adequate statistical precision. This implies that one wants a relatively fast end-to-end simulation tool for rapid accumulation of the results with good statistical accuracy. Initially, we plan to do simulations with a few million particles per run. We plan to convert PARMTEQ to run on high performance computers, using parallel computing. Initially, we will run on the NERSC (National Energy Research Scientific Computing Center) computing facility at LBNL, where we already have familiarity and experience with that system.

The procedure we are adopting for the initial parallel computation is a relatively simple one called the particle decomposition method. Assuming that we are using N processors, the beam particles are initially distributed uniformly over these processors; each processor tracks the dynamics of its own subset of the particles. If the space-charge forces are not included in the simulation, the particles move independently, and the simulation can be performed as a fully parallel computation. The speed of the computation will be increased by nearly a factor N .

When the space-charge forces are turned on, all the particles interact; this affects the parallel computation efficiency. To explain how the space charge forces are handled in a parallel computation using the particle decomposition method, we can look at one cycle of the space-charge calculation. First, a spatial grid or mesh is superimposed on all the particles being tracked. Each processor has an identical copy of the full grid, and each deposits its particles on its copy. After this is completed, the accumulated charge distribution from each processor is made available to all the processors. All these distributions are added together by every processor in such a way that when this is completed, every processor has an identical copy of the total charge density on the full grid. Then, each processor solves the Poisson equation using the full charge distribution to obtain the total electric potential and the total field components at each of the mesh points.

The next step is for each processor to interpolate the fields on the mesh points to the locations of the particles that belong to that processor. Then, each particle in each processor gets a kick and is advanced to a new position. The field interpolations and kicks are done in parallel by all the processors. A typical efficiency for parallel computation using this method is expected to be about 25 to 30%, when space charge is included, which is still a significant improvement in computational speed over that of a single processor. For example, with 128 processors, we anticipate that the computational speed would increase by about a factor of 32 to 42. The main advantage of this approach to parallel computation in the presence of space-charge forces is its simplicity. Ideally, the existing space-charge subroutine used for conventional serial computations, needs to

be modified only by the introduction of a command that adds the charge distributions from each of the processors to accumulate the total charge distribution.

Status of Simulation Code Development for LEBT and RFQ

Our simulation code development work began within the past three months. The work for part 1 of the project has been divided into three steps. First, we are adding the required multicharge-state physics changes to the standard version of PARMTEQ that runs on our desktop computers. Second, we are installing the standard version of the PARMTEQ code on the NERSC supercomputer, and will modify it to run in parallel mode. The third step will be to insert the same physics changes already incorporated in the desktop computer version into the modified parallel version of PARMTEQ that runs at NERSC.

At present, the desktop version of the standard PARMTEQ code has been modified to transport and accelerate beams with two charge states, including space charge, through the LEBT and RFQ. Fig. 1 shows PARMTEQ simulation results with phase-space plots and rms sizes for a two-charge-state simulation run through a RIA LEBT and RFQ design. Space-charge forces have been included. In this simulation, the two-charge-state beam is transported in the LEBT, bunched with a multiharmonic buncher, and accelerated to the end of the RIA RFQ.

In addition, we have installed the standard version of the PARMTEQ code at NERSC, and simulation results at NERSC have been benchmarked against the PARMTEQ results of the version that runs on a desktop computer. This work has involved many tasks for establishing compatibility, such as deleting the original Windows-based graphics commands, and modifying the I/O statements appropriate for use of ASCII format for all files. The next step for the PARMTEQ version at NERSC is to insert the multicharge-state physics changes, and insert the commands required for parallel computing. Afterwards, we will carry out a systematic program of benchmarking of the rms results from the new version of PARMTEQ against the existing TRACK and LANA codes.

Conclusions

The objective of the work is to develop an end-to-end multiparticle parallel beam-dynamics simulation tool suitable for high-statistics computation of beam dynamics and beam losses in the RIA driver linac. This paper described part 1 of the project, which is to develop a multiparticle parallel code to model the multicharge-state beam dynamics, including space charge, in the critical low-velocity region of the linac that includes the low-energy beam transport (LEBT), the radiofrequency quadrupole (RFQ), and the medium-energy transport section that matches the beam into the main superconducting linac. An accompanying paper at this workshop describes the work of part 2 [16], to develop the simulation code for the superconducting linac, including the strippers and the magnetic chicane sections required for charge-state selection, rebunching, and matching of the multicharge beams. Our approach for part 1 is to modify the well-known and widely-used PARMTEQ code for multicharge-state parallel beam-dynamics simulations. The present progress for part 1 includes the implementation of two-charge-state beam

dynamics with space charge to the desktop version of PARMTEQ. In addition, we have installed a version of the standard PARMTEQ code at the NERSC supercomputer, and have benchmarked it against the desktop computer version. Future work will include 1) introduction of the same multicharge-state physics changes at NERSC, and 2) implementation of a parallel computing capability to the NERSC version. This will be followed by a systematic benchmarking of both the modified desktop and NERSC versions against the rms results of the TRACK and LANA codes. Then, we will apply the end-to-end simulation tool to obtain beam-loss computations for different designs.

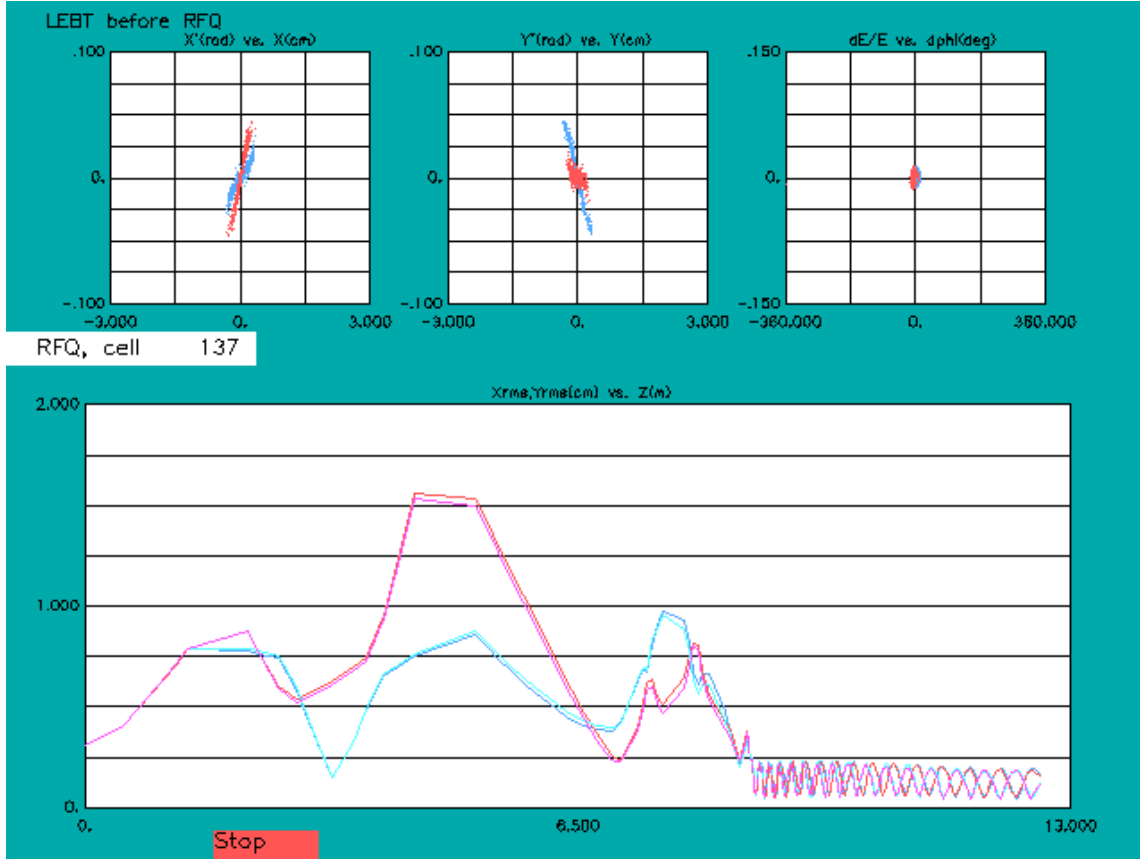


Fig. 1. Three phase space plots (shown at top) at end of the RFQ for a beam with two uranium charge states, $q=28$ in blue and $q=29$ in red, for a simulation through a RIA LEBT and RFQ design. Rms beam sizes in x and y are shown at bottom. The red curves in the lower plot show rms values of x for the two charge states, and the blue curves show y.

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